



Are the Bulge C-stars in the Sagittarius dwarf galaxy?

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Abstract. Part of the mystery around the Bulge carbon stars from Azzopardi et al. (1991) is solved, if they are related to the Sagittarius dwarf galaxy. The carbon stars are in that case not metal-rich as previously thought, but they have a metallicity comparable to the LMC, with an age between 0.1–1 Gyr. A significant fraction of the carbon stars still have luminosities fainter than the lower LMC limit of $M_{bol} \simeq -3^m5$. A similar trend is present among some of the carbon stars found in other dwarf spheroidals, but they do not reach a limit as faint as $M_{bol} \simeq -1^m4$ found for the SMC. At present, the TP-AGB models cannot explain the origin of carbon stars with $M_{bol} > -3^m5$ through a single-star evolution scenario, even if they form immediately after entering the TP-AGB phase. Mass transfer through binary evolution is suggested as a possible scenario to explain the origin of these low luminosity carbon stars.

Key words: Stars: carbon stars – evolution – Hertzsprung-Russell (HR) diagram — galaxies: individual: Sagittarius dwarf – Local Group – Galaxy center

1. Introduction

1.1. Bulge carbon stars

For a long time carbon stars are searched in the direction of the Galactic Centre. From a low dispersion, near infrared grism survey a total of five carbon stars were found amid 2187 M-giants (Blanco et al. 1978, McCarthy et al. 1983 and Blanco & Terndrup 1989). The stars are mainly identified by the CN bands at 7945, 8125, and 8320 Å. Azzopardi et al. (1985ab; 1986) demonstrated that additional, especially blue carbon stars can be found with the strong Swan C₂ bands (4737 and 5165 Å) in the spectral range 4350–5300 Å. Using this technique, Azzopardi et al. (1985b, 1988; the latter is hereafter referred to as ALR88) found 33 carbon stars in 8 different fields of the Galactic Bulge. Near-IR photometry and medium-low resolution spectra have been obtained for these carbon stars

(Azzopardi et al. 1991 – hereafter referred to as ALRW91, Tyson & Rich 1991, Westerlund et al. 1991). These stars show similarities with the low- to medium bolometric luminosity SMC carbon stars, but the galactic carbon stars have stronger NaD doublets. Various studies suggest that a wide metallicity range is present in the bulge (Whitford & Rich 1983, Rich 1988 & 1990, Geisler et al. 1992, McWilliam & Rich 1994, Ng 1994, Bertelli et al. 1995, Ng et al. 1995 & 1996, Sadler et al. 1996). According to ALR88 the carbon stars are expected to be metal-rich if they belong to the Bulge.

1.2. Sagittarius dwarf galaxy

The serendipitous identification of the Sagittarius dwarf galaxy (SDG) was made by Ibata et al. (1994, 1995; hereafter respectively referred to as IGI94 and IGI95). It is the closest dwarf spheroidal and moves away from us at about 160 km/s. Accurate distance determinations from RR Lyrae stars belonging to this galaxy range from 22.0–27.3 kpc (Alcock et al. 1997; Alard 1996; Mateo et al. 1995ab, 1996; Ng & Schultheis 1997 – hereafter referred to as NS97). The photometric metallicity estimates made thus far depend heavily on the assumed age and the values for [Fe/H] range from −0.5 to −1.8. The mean age (10–12 Gyr) and metallicity ([Fe/H] = −1.5) adopted is a trade-off, such that the age conveniently allows for the presence RR Lyrae and carbon stars (Ibata et al. 1997). IGI95 identified four carbon stars belonging to this galaxy, Whitelock et al. (1996, hereafter referred to as WIC96) performed a near-IR study of 26 candidates, and NS97 identified one more carbon star in the outer edge of the dwarf galaxy. The next section deals with how the Bulge carbon stars mentioned above are related to the (candidate) carbon stars from the dwarf galaxy.

1.3. A clue?

A supposedly high metallicity lead Tyson & Rich (1991) and Westerlund et al. (1991) to suggest that the Bulge carbon stars should be old and posses a mass of about $0.8 M_{\odot}$, while evolutionary calculations (Boothroyd et al.

1993, Groenewegen & de Jong 1993, Groenewegen et al. 1995, Marigo et al. 1996ab) demonstrate that the initial mass of carbon stars is at least $1.2 M_{\odot}$ ($t \lesssim 4$ Gyr) for $Z = 0.008$. Furthermore, the initial mass increases towards higher metallicity and decreases towards lower metallicity (Lattanzio 1989). The Bulge carbon stars are a mystery (Lequeux 1990, Tyson & Rich 1991, Westerlund et al. 1991, Chiosi et al. 1992, Azzopardi 1994), because they are in bolometric luminosity about 2^m5 too faint to be regarded as genuine AGB (Asymptotic Giant Branch) stars, if located in the metal-rich Bulge.

NS97 compiled a catalogue of candidate RR Lyrae and long period variables (LPVs) in the outer edge of the SDG. After de-reddening of the K-band magnitudes for the candidate LPVs, the period- K_0 relation for the Mira variables from the Sgr I field in the Bulge from Glass et al. (1995) put these stars at 25.7 kpc. This distance is in good agreement with the distance obtained from the RR Lyrae stars found in the same field. One of the LPVs is a carbon star. The difference between the distance modulus of the dwarf galaxy and the Galactic Centre at 8 kpc is $\sim 2^m5$. This lead to the suggestion that the Bulge carbon stars could actually be located in the dwarf galaxy, whose presence was unknown at the time the carbon stars were identified. This would solve the standing question about the origin of the ‘bulge’ carbon stars.

The possibility that the ‘bulge’ carbon stars could be member of the SDG is analyzed. The organization of the paper is as follows. In Sect. 2 the formerly Bulge carbon from ALRW91 are placed in a CMD (colour-magnitude diagram) at the distance of the SDG. A comparison is made with the near-IR magnitudes and colours from actual and candidate carbon star members from the dwarf galaxy (WIC96, NS97). In Sect. 3 isochrones are placed in the CMD and it is demonstrated that the majority of the ALRW91 carbon stars are still fainter than the tip of the red giant branch. A discussion of the results is given in Sect. 4. Some stars are too faint, even if carbon stars are formed immediately after they enter the TP-AGB phase, and a possible binary evolution origin is suggested for some of the carbon stars fainter than the red giant branch tip. Arguments are given that the expected number of carbon stars related to the SDG is at least two times larger. The results are summarized in Sect. 5.

2. Data and method

2.1. Near-infrared photometry

The near-IR photometry of the Bulge carbon stars presented by ALRW91 was reduced to the standards from the homogenized ESO photometric system proposed by Koornneef et al. (1983ab). Bouchet et al. (1991) found in this system no systematic differences in the magnitudes from the standards observed at ESO in the period 1983–1989.

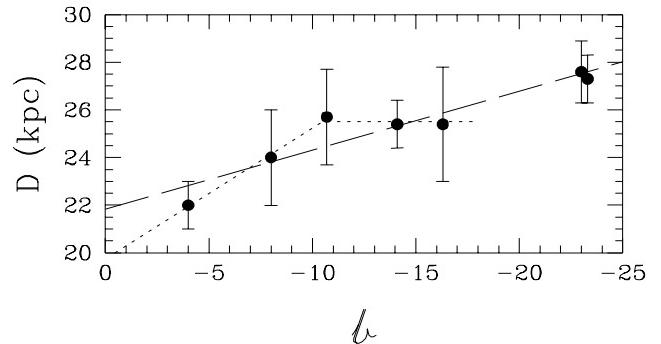


Fig. 1. The distance of the Sagittarius dwarf galaxy determined for various galactic latitudes. The dashed line refers to an unweighted linear least squares fit for the points, while the long-dashed line shows a two section fit drawn through the points

The near-IR photometry from WIC96 with the SAAO 1.9m telescope is appropriately transformed to the ESO system (Hron et al. 1997). Note, that in general many transformations from SAAO to the ESO near-IR system refer to the transformation from the system defined by Glass (1974) or Carter (1990) to an older ESO system defined by Engels et al. (1981) and Wamsteker (1981).

2.2. Extinction and distance

The extinction for the Bulge carbon stars is not homogeneous. For each field defined by ALRW91 a general correction is applied to all stars. Instead of $A_V = 1^m87$ (Glass et al. 1995) an extinction of $A_V = 1^m71$ is adopted for the Sgr I field. It is the average value from Walker & Mack (1986) and Terndrup et al. (1990). For Baade’s Window field around NGC 6522 $A_V = 1^m50$. This value was obtained by Ng et al. (1996) from the (V,V-I) CMD obtained by the OGLE (Optical Gravitational Lensing Experiment, see Paczyński et al. 1994 for details) and is in good agreement with average value $E(B-V) = 0^m49$ determined for this field. For the extended clear region around and near NGC 6558 the same value as used by ALR88, $E(B-V) = 0^m41$ or $A_V = 1^m27$ from Zinn (1980), is adopted. No actual determinations of the extinction are found for the field intermediate to NGC 6522 and NGC 6558 and $A_V = 1^m38$ is adopted. For the remaining Bulge fields ($b < -8^{\circ}0$) a relation (Blommaert 1992, Schultheis et al. 1997) based on the reddening map constructed by Wesselink (1987) from the colour excess of the RR Lyrae stars at minimum light, is used: $A_V = 0.104 b + 1.58$, where b is the galactic latitude. The value $A_V = 0^m48$ obtained by Mateo et al. (1995) is adopted for the stars in the SDG observed by WIC96. The extinction in the near-IR passbands is determined under the assumption that $A_J/A_V = 0.282$, $A_H/A_V = 0.175$, and $A_K/A_V = 0.112$ (Rieke & Lebofsky 1985).

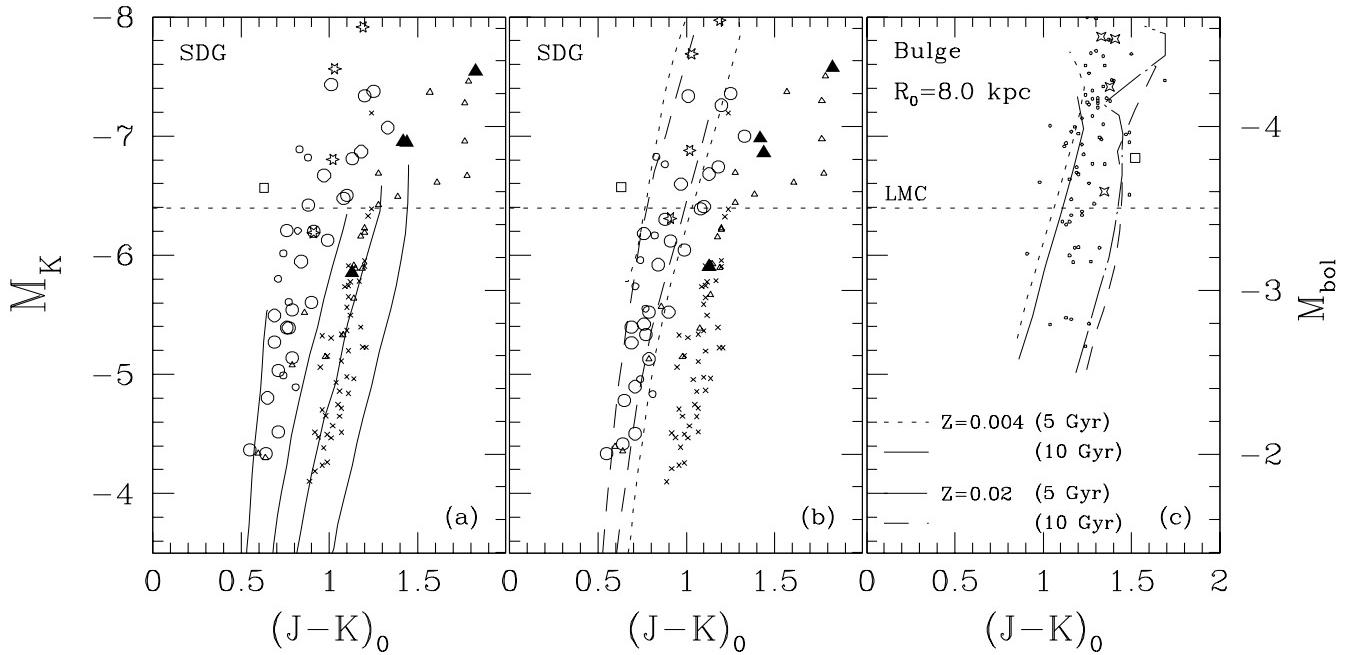


Fig. 2. Panel (a & b) The ALRW91 carbon stars placed at the distance of the Sagittarius dwarf galaxy (open circles; small open circles are used to indicate a larger uncertainty in the extinction adopted), together with the carbon stars from IGI95 (filled triangles). Open triangles and crosses are used for respectively the candidate carbon stars and giant branch stars of the dwarf galaxy observed by WIC96. The open square indicates the carbon stars S283 found by NS97 among the variables studied by Plaut (1971) and Wesselink (1987). The dotted horizontal line indicates the observational lower LMC limit at which carbon stars are found, while the lower magnitude limit corresponds with the SMC limit (Azzopardi 1994). The difference between panel (a) and (b) is the method used to assign a distance to each star, see Sect. 2.3. Panel (c) shows the stars which are possibly located in the Bulge. The open crosses indicate the giant branch stars observed by WIC96, the open square is a carbon star (L199, unpublished) found among the variables studied by Plaut (1971) and Wesselink (1987), and the dots show for comparison the location of the semiregular and Mira variables selected from respectively Schultheis et al. (1997) and Blommaert (1992). The isochrones (Bertelli et al. 1994; only for $\log T_{\text{eff}} < 3.70$) displayed in the three panels are as follows: a) 10 Gyr RGBs for $Z = 0.0004, 0.004, 0.008$, and 0.020 ; b) 1 and 10 Gyr AGBs for $Z = 0.001$ (long-dashed line) and 0.1 and 1 Gyr AGBs for $Z = 0.008$ (dotted line); and c) 5 and 10 Gyr AGBs for $Z = 0.004$ (dotted and solid line) and $Z = 0.02$ (dot-dashed and dashed line). See Sect. 3.1 for additional details about the magnitude and the colour transformations.

Note that the left vertical axes in each panel give the K -magnitude scale, while the right vertical axes indicate the M_{bol} -scale

The distance determined with RR Lyrae stars for the SDG ranges from 22.0–27.3 kpc. Figure 1 shows that these distances are actually correlated with the galactic latitude at which they were determined. Additional distance determinations (Sarajedini&Layden 1995 – hereafter referred to as SL95, Fahlman et al. 1996) obtained with other methods were added to this figure. An unweighted linear least squares fit through those distances gives $D(\text{kpc}) = 21.83 - 0.25 b$. Figure 1 also shows a two section line drawn through these points.

2.3. Colour-magnitude diagram

Figure 2a shows the de-reddened CMD. A distance correction with the linear least squares line was applied to all the stars to reduce the scatter due to differential distance effects. Figure 2b shows the diagram with the distances corrected with the two section line. There is no significant difference between the Figs. 2a & 2b. Some stars are

very bright. In SDG their M_{bol} would range from -6^m0 to -7^m0 . They could be bright members of SDG or they could be located in the Bulge and have a lower luminosity. For a graphical purpose those stars are placed in Fig. 2c at a distance of 8.0 kpc. A sample of LPVs from Schultheis et al. (1997) are included in panel 2c. The dotted line in Figs. 2a–c is the lower LMC limit at which carbon stars are found, while the lower magnitude boundary corresponds with the SMC limit.

Figures 2a&b show that three of the four IGI95 carbon stars observed by WIC96 form an extension to the ALRW91 sequence of carbon stars. This clearly is a strong indication that the ALRW91 carbon stars belong to the SDG. The fourth carbon star (star C1 from WIC96) appears to be redder and located in the parallel sequence formed by the giant branch stars. It is not clear if this is due to a mis-identification in the photometry with another redder, nearby star. The finding chart provided from WIC96 does not rule out this possibility. The figure fur-

ther shows that eight (#s 1–3, 5, 6, 12, 15, 21) out of the 26 stars from WIC96 are highly eligible carbon star candidates, because they are located on the combined ALRW91 & WIC96 carbon star sequence.

A significant number of the ALRW91 carbon stars are located below the LMC limit at which carbon stars are found. This limit might be related to a low metallicity of the stars, but in Sect. 4.1 it is argued that this is not the case. A similar trend is present among some of the carbon stars found in other dwarf spheroidals (see Fig. 2b from WIC96). However, Azzopardi et al. (1997) found carbon stars with $M_{bol} \simeq -1^m 2$ in the Fornax dwarf galaxy, assuming $(m-M)_0 = 21^m 0$. This is even fainter than the present limit $M_{bol} \simeq -2^m 0$ for the ‘bulge’ carbon stars if located in the SDG and $M_{bol} \simeq -1^m 4$ for the SMC carbon stars (Azzopardi 1994; Westerlund et al. 1993, 1995). Four LPVs, most likely belonging to the dwarf galaxy (NS97), are included in this figure. Note that they are the first Mira and the semiregular variables found belonging to the SDG. In fact, they are the first LPVs discovered in a dwarf spheroidal galaxy. Two LPVs are located inside the carbon star sequence, while the other two form at $M_K < -7^m 5$ a blue extension to the carbon sequence.

3. Models

3.1. Conversion: theoretical → observational plane

The transformation of the bolometric magnitude to the K-magnitude scale in Fig. 2 is obtained from the period-luminosity (PL- and PK-) relation of carbon Miras (Groenewegen & Whitelock 1996, hereafter referred to as GW96). Transformed to the ESO photometric system this gives: $M_K = 1.37M_{bol} - 1.58$. The actual transformation from the bolometric magnitude to a K-magnitude in the models shown in Fig. 2 is achieved with the relation provided by Suntzeff et al. (1993):

$$\begin{aligned} M_K &= M_{bol} - BC_K, \\ BC_K &= 1.00 + 2.076(J - K)_0 - 0.463(J - K)_0^2. \end{aligned}$$

The relation is valid for $0^m 3 < (J - K) < 2^m 3$ and was obtained from a fit to the $(J - K, BC_K)$ relation given by Frogel et al. (1980). The bolometric magnitude was obtained from the numerical integration of the broadband flux distributions of the galactic carbon stars observed by Men-doza & Johnson (1965). The same bolometric corrections are applied to non-carbon stars. Figure 2 from Frogel et al. (1980) shows that the differences are at most $\sim 0^m 2$.

The conversion from $\log T_{\text{eff}}$ to $(J - K)_0$ is established from an empirical relation derived by Ng et al. (1997), based on giant stars with a spectral type ranging from late G to late M. The effective temperatures for these stars were obtained from angular diameter measurements. The empirical $\log T_{\text{eff}}/(J - K)_0$ relation takes into account a small shift in colour as a function of metallicity. The relations, provided for the metallicity $Z = 0.004$ and $Z = 0.024$,

are logarithmically interpolated for $Z \geq 0.004$ and the $Z = 0.004$ relation is applied for lower metallicities. Although some uncertainty is present due to the fact that this relation is not based on carbon stars, the differences will not be too large as long as the colours are not too red. The empirical relation covers conveniently the observed colour range of the carbon stars.

3.2. Isochrones

In Figs. 2a–c some isochrones from Bertelli et al. (1994) are displayed. Fig. 2a shows the RGB for an age of 10 Gyr for various metallicities and Fig. 2b & 2c show the AGB for different age and metallicities. Figure 2a demonstrates that if one assumes a fixed age then a large metallicity spread could be present among the SDG stars. Given the uncertainties, the GB stars likely have a metallicity of $Z = 0.008$, comparable to the LMC. Figure 2b demonstrates that difficulties are present to distinguish 1 & 10 Gyr isochrones for the AGBs with $Z = 0.001$ from those with a 0.1 & 1 gyr age for $Z = 0.008$. The isochrones in Fig 2c show that the colour difference between 5 and 10 Gyr populations with the same metallicity is quite small compared to the colour difference due to a large metallicity range.

4. Discussion

4.1. Metallicity and age

The isochrones in Fig. 2a indicate that the metallicity of the old population in the SDG is $Z \simeq 0.008$. This is quite high, but within the uncertainties comparable with $[\text{Fe}/\text{H}] = -0.52 \pm 0.09$ obtained by SL95 from a photometric study of a (V,V-I) CMD. This is in contrast with values $[\text{Fe}/\text{H}] \lesssim -0.7$ obtained with different methods (IGI94, IGI95, Ibata et al. 1997, Fahlman et al. 1996, Mateo et al. 1995 & 1996, WIC96, Marconi et al. 1997).

SL95 found an indication of the possible existence of a $[\text{Fe}/\text{H}] = -1.3$ (i.e. $Z = 0.001$) component in the dwarf galaxy. With such a metallicity the age of the carbon stars is somewhere between 1 and 10 Gyr, see Fig. 2b. Figure 2a already shows that there is an old component with $Z = 0.008$ and an age around 10 Gyr. If there is a rather smooth age range present for $Z = 0.001$, then why are the younger stars absent among the RGB stars with $Z = 0.008$? Furthermore, why should the metallicity decreases towards younger age? From a close box model one expects an increasing metallicity towards younger age. All together this does not favour a metallicity of $Z = 0.001$. If on the other hand, the metallicity for the carbon stars is $Z = 0.008$ then we are apparently dealing with two different age populations. The carbon stars would in this case reflect a very recent star formation burst in this galaxy, while the major stellar population has an age ~ 10 Gyr. An almost zero metallicity enrichment is in agreement

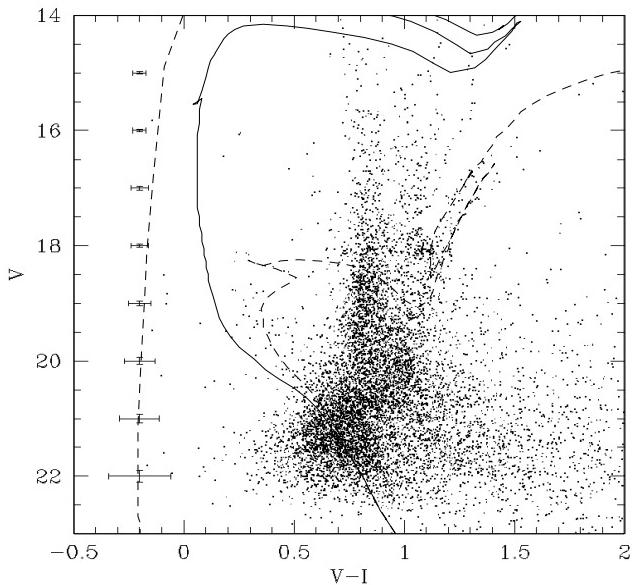


Fig. 3. CMD of SDG stars in field 1 from Marconi et al. (1997) with an overlay of $Z=0.008$ isochrones of 0.1 Gyr (solid line) and 1 Gyr (dashed line) from Bertelli et al. (1994). The dashed line between $(V,V-I)=(14^m 0, 0^m 0)$ and $(V,V-I)=(23^m 0, -0^m 2)$ is the white dwarf cooling sequence from the 1 Gyr isochrone. An extinction of $A_V=0^m 48$ and a distance modulus of $17^m 02$ (Mateo et al. 1995) have been adopted for the isochrones

with the multiple starburst Carina dwarf spheroidal studied by Schmecker-Hane et al. (1996).

A young age could be independently confirmed through the detection of Cepheids in the SDG. Mateo et al. (1995) report the possible detection of an anomalous Cepheid and suggest that the SDG might contain a considerable number of these stars.

Just as in this study, SL95 would not be able to distinguish from their CMD the difference between a very young $Z=0.008$ population from an older $Z=0.001$ population. So the present interpretation is not in contradiction with their results. An indication that we are indeed dealing with young stellar populations is present in the CMDs from Marconi et al. (1997). In Fig. 3 (i.e. Marconi's et al. Fig. 2) the 0.1 Gyr and 1.0 Gyr isochrones demonstrate clearly the presence of a young population above the main sequence turn-off of the old stellar population from the SDG. It is not clear though, why the two distinct age populations advocated above are not present in the CMDs analyzed by Fahlman et al. (1996). Possibly the number of stars involved are too small to be conclusive and the analysis has to be repeated with a larger number of stars in the background of the globular clusters.

From the considerations outlined above it is concluded that the metallicity of the SDG stars is $Z\simeq 0.008$. The age of the ALRW91 carbon stars is with this metallicity

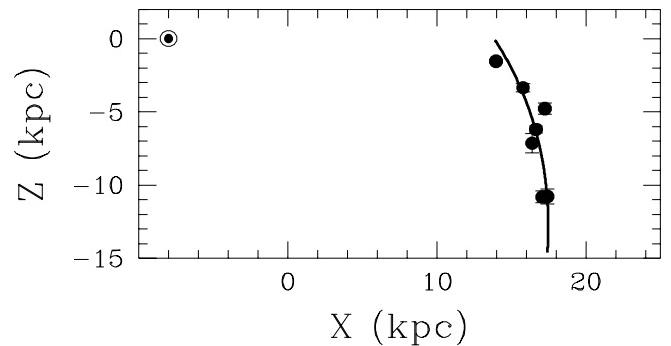


Fig. 4. The course of the Sagittarius dwarf galaxy projected on the $x-z$ plane. The radial velocity of the galaxy indicates that it is moving away from us. Together with the indicated course this implies that the galaxy crossed quite recently the galactic disc. The position of the Sun is indicated by \odot

young than 1 Gyr. A second distinct population is present with an age around 10 Gyr.

If a star formation burst is related with a passage through the galactic disc then an age as young as 0.1 Gyr would confirm the assertion that the SDG already passed through the disc and is currently moving away from our Galaxy (Alcock et al. 1997, NS97). Figure 4 indicates that this should indeed be the case. The absence of populations with intermediate ages separated by approximately 1 Gyr appears to rule out the orbital period suggested by Johnston et al. (1995), Velázquez & White (1995) and Ibata et al. (1997). Johnston et al. however pointed out that the existing observations were not sufficient to put limits on the orbit or initial state of the SDG.

4.2. Are the ‘bulge’ carbon stars on the TP-AGB ?

In the current understanding of stellar evolution theory carbon stars are formed at the third dredge-up at the TP-AGB (thermally pulsing asymptotic giant branch) phase, in which the stellar surface is enriched with ^{12}C . Carbon stars cannot be formed before the TP-AGB phase. In the LMC the majority of the stars are located above the tip of the RGB (red giant branch), but they can be located $\sim 1^m 0$ below RGB tip for 20%–30% of its interpulse period (see Marigo et al. 1996ab and references cited therein).

At the distance of the SDG a considerable fraction of the ALRW91 carbon stars are located well below the tip of the RGB. Figure 5 demonstrates that even if carbon stars can form directly after they enter the TP-AGB phase, the presence of a fraction of those carbon stars cannot be explained. These stars are likely formed through another mechanism not accounted for in the ‘standard theory’ for the formation of carbon stars in the TP-AGB phase. The sequence of carbon stars parallel to the giant branch suggest that they are either RGB or early AGB stars. It ap-

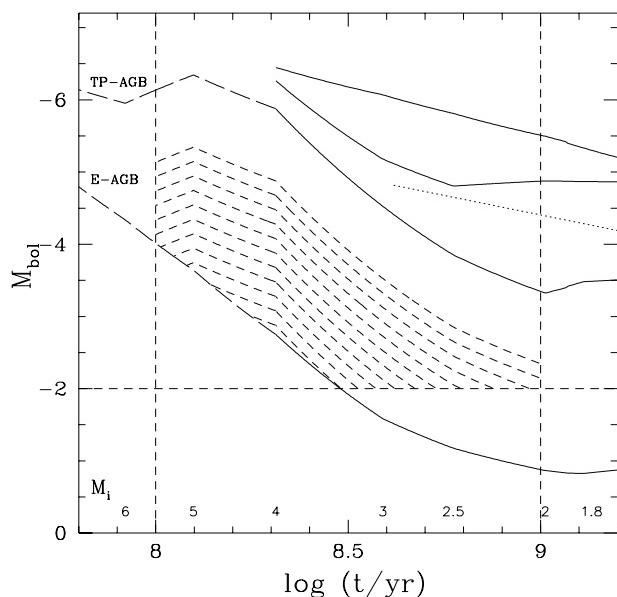


Fig. 5. Four solid lines are displayed for the LMC, indicating the start of the E-AGB, TP-AGB, the transition from M- to C-type stars and the end of the AGB evolution (see Marigo et al. 1996b for details). Above the dotted line carbon stars with masses in the range $1.2 - 3.0 M_{\odot}$ have a 90% detection probability. M_i is the initial mass of the carbon star. The dashed, horizontal line is the limiting magnitude for the SDG carbon stars and the dashed, vertical lines indicate the age range for the SDG stars (see Sect. 4.1) if $Z \approx 0.008$. The shaded area indicate the region in which the presence of carbon stars cannot be explained with a TP-AGB star, see Sect. 4.2

parently contradicts our theoretical understanding about the formation process of carbon stars.

ALR88 suggested two possible scenarios. Westerlund et al. (1991) favoured the scenario where a very effective mixing occurs at an early phase on the ascend to the TP-AGB. Since this cannot be the case for even the faintest carbon stars related to the SDG, the scenario of mass transfer through binary evolution is favoured for the formation of the low luminosity carbon stars. The same scenario explains the observations of dwarf carbon stars (see Green 1997 and references cited therein).

In case of mass transfer through binary evolution, the primary star evolved through the TP-AGB phase and transferred a significant part of its ^{12}C enriched envelope to the secondary. The primary evolved away from the AGB and is a white dwarf now and the secondary is the presently observed carbon star. The fully convective envelope of stars at the RGB or AGB would dilute $^{12}\text{C}/^{13}\text{C}$ ratio. The dilution is proportional to the time elapsed since the primary deposited part of its envelope on the secondary star. The dilution should increase towards larger distances from the galactic disc (see Figs. 1 & 4). The NaD equivalent width and the CN line strength ob-

tained from spectra for the carbon stars by Tyson & Rich (1991, see their Fig. 3) would support this assertion. For comparable envelope masses the dilution will be at least a factor 2. If the metallicity is about $Z = 0.008$ then the mass transfer should have occurred recently, indicating that the difference of the initial mass between the primary and secondary is very small. A metallicity of $Z = 0.008$ is in addition high enough to explain the strong NaD features found present among the carbon stars.

McClure (1984) showed that CH stars are binaries, some of them are long-period systems. Suntzeff et al. (1993) argue that the CH stars in the LMC, with M_{bol} ranging from -5^m3 to -6^m5 , have an age near 0.1 Gyr. Some of the CH stars could well be the predecessors of the SDG carbon stars. If L199 is a CH star and the four giant stars observed by WIC96 are related to the SDG they have $M_{bol} \approx 6^m5$. A binary nature of those stars would strongly support the evolution scenario outlined above.

In Fig. 6 the near-infrared photometry of the ‘bulge’ carbon stars are compared with the photometry for the obtained for a sample of SMC carbon stars (Westerlund et al. 1995). For the SMC carbon stars we adopted $(m-M)_0 = 18^m9$ and $E(B-V) = 0^m09$ (Westerlund 1997). Westerlund et al. (1991, 1993, 1995) noted that the most luminous ‘bulge’ and SMC carbon stars have comparable C_2 and CN values, whereas the fainter ‘bulge’ stars are more similar to the main bulk of faint SMC carbon stars. This result is not surprising anymore if, as argued in this paper, the ‘bulge’ carbon stars are indeed related to the SDG. Figure 6 indicates that the former ‘bulge’ carbon stars have luminosities almost comparable to the SMC carbon stars. The ALRW91 carbon stars form a parallel sequence with the SMC stars. As argued in Sect. 4.1 the ALRW91 carbon stars likely have a metallicity $Z \approx 0.008$, while the SMC carbon stars are expected to be metal poorer. The SMC sequence ought to be bluer than the SDG sequence, if the carbon stars have a similar age. This however is not the case and the carbon stars therefore do not originate from a population with a similar age. The colours of both sequences can be explained when the SMC carbon stars evolved from an older stellar population.

4.3. Are there more SDG carbon stars ?

It is an important issue to check if more carbon stars from the dwarf galaxy can be found in other fields. From NS97 a crude estimate of about 1/2 is found for the ratio of LPVs versus the RR Lyrae stars of Bailey type *ab*. About one out of six LPVs could be a carbon star. This is however a lower limit, because the sample from NS97 is biased towards the brighter stars. The observations were mainly limited due to the instrumental setup and the telescope size and no reliable data was obtained for some of the fainter, suspected carbon stars in the sample.

About 29 more carbon stars with $M_K \lesssim -6^m5$ might be found among the long period variables in the DUO

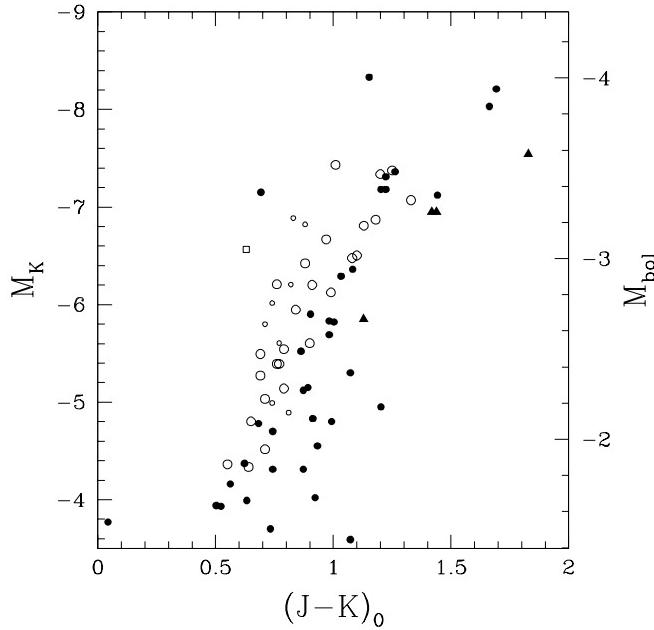


Fig. 6. A comparison between the ‘bulge’ carbon stars (symbols as in Fig. 2) if located in the SDG and the SMC carbon stars (Westerlund et al. 1995; filled dots)

(Disc Unseen Objects; see Alard 1996 and references cited therein), MACHO (Massive Astrophysical Compact Halo Objects; see references in Alcock 1997), and even the OGLE (see references in Paczyński et al. 1994) databases. However, considerably more candidate carbon might be present among the stars with $-6^m5 < M_K < -4^m0$. Extrapolating the carbon star PK-relation from GW96 indicates that if some of these stars are variables, they might be found among the variables with periods in the range from 40–130 days. An additional result would be a significant increase of the number of LPVs related to the SDG.

Another way to estimate the expected number of carbon stars for the SDG is through the fuel consumption theorem (see Renzini & Buzzoni 1983, 1986 for details). For a population of young stars we have the relation: $N_* = 5 \times 10^{-12} \times \Delta t \times L_{bol}$, where $L_{bol} \sim 4 \times 10^7 L_\odot$ (Mateo et al. 1996; $L_{bol} \simeq 2L_V$) and $\Delta t \simeq 5 \times 10^5$ yr. About 100 carbon stars are thus expected. The number is a lower limit, because the full extent of the SDG has not been taken into account and the bolometric luminosity has therefore been underestimated. Moreover, the duration over which carbon stars can be observed is prolonged through mass transfer from binary evolution. All together the expected number of SDG carbon stars might be about 10 times larger than hitherto found.

4.4. What about the RR Lyrae stars ?

A significant amount of RR Lyrae stars have been found and have been used to constrain the distance towards the SDG, see Sect. 2.2. As mentioned in Sect. 1.3 the distance

of the LPVs is consistent with the RR Lyrae found in the same field (NS97). The LPVs likely have an age comparable to the age of the carbon stars and a metallicity of $Z \simeq 0.008$.

The metallicity of the RR Lyrae stars are expected to be considerably smaller, say between $Z = 0.0004$ – 0.001 . The GB stars from the parent population appears to be absent in Fig. 2a. This could be due to a bias in the selection of the GB stars, confusion of an old, metal-poor population with the GB from a 0.1–1.0 Gyr population with $Z = 0.008$, or the parent population of the RR Lyrae stars has a metallicity close to $Z = 0.008$. In addition, it is not clear how the SDG RR Lyrae stars are related to, or even might originated from the four globular clusters located at the SDG distance (Da Costa & Armandroff 1995).

The present situation is rather confusing. It is not clear at all what the actual metallicity of the parent population of the SDG RR Lyrae stars is. A thorough analysis of deep CMDs, similar to those from Marconi et al. (1997), with a significant number of stars near the main sequence turn-off is required to determine the age and metallicity of the oldest population in the SDG.

4.5. A twist of fate ?

4.5.1. Radial velocities

The radial velocities of the ‘bulge’ carbon stars would provide an independent verification of the photometric analysis presented here, concerning membership of the SDG. Tyson & Rich (1991) determined the radial velocities for 33 stars from the ALRW91 sample. Their radial velocities would support only for a small number of stars the suggestion that the ALRW91 carbon stars are actually located in the SDG, while the majority of the stars are moving towards us and could be Bulge members.

The spectroscopic results related to the CN line strength and the NaD equivalent width would support membership to the SDG combined with a binary evolution scenario for these stars. Membership of the Bulge does not make sense, because there is in that case no trace of a predecessor, i.e. a brighter population of carbon stars (see Azzopardi 1994, Fig. 2). One could argue that an independent verification of the radial velocities, with a zeropoint based on other stars than the one template star ROA 153 used by Tyson & Rich (1991), might shed some light on the present contradictory results.

However, if both the photometric and spectroscopic analysis are correct then the ALRW91 carbon stars are related to the SDG. Some stars move away from us in the same direction as the SDG, while others move towards us, away from the SDG. This does not necessarily imply that we observe the ongoing disruption of the SDG. It is not clear if an encounter of the SDG with the galactic disc could result in the bifurcation of the radial velocity distribution for stars formed or located in the tidal tail. The numeri-

cal simulations from Johnston et al. (1995, their Fig. 10c and 10d) do show that the stars from a 1 Gyr old, tidal stream have a different radial velocity when observed at about 10° further along the orbit. But the presence of a moving group is not obvious, since its velocity distribution is not easily distinguished from halo or bulge stars.

4.5.2. Completeness limits

An intriguing point is that in the LMC carbon stars have not been identified with $M_K \lesssim -6^m5$, while they are found in some dwarf spheroidal galaxies. The majority of the carbon stars were found from green or near-IR grism surveys (see Azzopardi et al. 1985b and references cited therein). It is not unlikely that the limiting magnitude mentioned above mark the completeness boundary due to heavily crowding. More carbon stars might be present, but they have not yet been identified. If they are variable, then the databases from the various microlensing projects (see contributions in Ferlet et al. 1997) will prove to be an important and valuable asset. A massive spectroscopic study combined with a near-IR photometry of the LPVs might reveal the carbon stars below the completeness boundary of the grism survey. Finding faint carbon stars in the LMC would provide a significant contribution to understand the origin of the low luminosity SDG carbon stars.

As an aside it is interesting that the colours of the ALRW91 & the SDG carbon stars have comparable colours with those found in other dwarf spheroidals. The question rises if this implies that they have comparable age and metallicities. If this is the case: a) where are the LPVs, and b) how would that change the star formation and chemical evolution history? As shown in Fig. 2b the blue giant branch sequence does not necessarily imply only an old, metal-poor population which is indistinguishable from a young, metal-richer giant branch.

5. Summary

- The ALRW91 carbon stars are likely not located in the Bulge, but are related to the SDG.
- The ALRW91 carbon stars are not metal-rich.
- The metallicity is about $Z = 0.008$ with an age between $0.1 - 1$ Gyr.
- A significant number of the ALRW91 carbon stars are located below the tip of the red giant branch.
- The origin of the carbon stars one magnitude below the red giant branch tip cannot be explained with the evolution of a TP-AGB star.
- The faint carbon stars likely originated through mass transfer from binary evolution.

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